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Secondary Loop Chilled Water In Super High-Rise

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This article presents the alternative design configurations for the secondary chilled water system in a super high-rise commercial building currently being constructed in Hong Kong. The original design configuration is evaluated and compared with an alternative design configuration concerning energy performance. Both configurations are implemented in this building to test and evaluate their operational performance.

Building and System Description

The building is a super high-rise building of approximately 1,608 ft (490 m) height (currently the tallest building in Hong Kong) and 3,455,215 ft^2 (321 000 m^2) of floor area. The building has a basement of four floors, a block building of six floors and a tower building of 98 floors. The basement is used mainly for parking. The block building from the ground floor to the fifth floor serves mainly as the commercial center including hotel ballrooms, shopping arcades, and arrival lobbies. The gross area is about 721,182 ft^2 (67 000 m^2). The tower building consists of 2,475,699 ft^2 (230 000 m^2) for commercial offices and a six-star hotel on the upper floors.

Figure 1 shows the central chiller and secondary chilled water system in this building. Six identical high voltage (10,000 V) centrifugal chillers located on the sixth floor with the capacity of 2,056 ton (7,230 kW) each and the nominal power consumption of 361 ton (1,270 kW) each at full load are used to supply the chiller water. The rated chilled water supply and return temperatures at the design condition are 42°F and 51°F (5.5°C and 10.5°C), respectively, while the rated condenser water inlet and outlet temperatures at the design condition are 90°F and 99°F (32°C and 37°C), respectively. The rated COP of each chiller at the design condition is 5.70. Each chiller is associated with one constant condenser water pump and one constant primary chilled water pump.

The water system is divided into four zones to avoid the chilled water pipelines and terminal units from suffering extremely high pressure, i.e., the highest static pressure of more than 4000 kPa (40 bar) and the designed working pressure of

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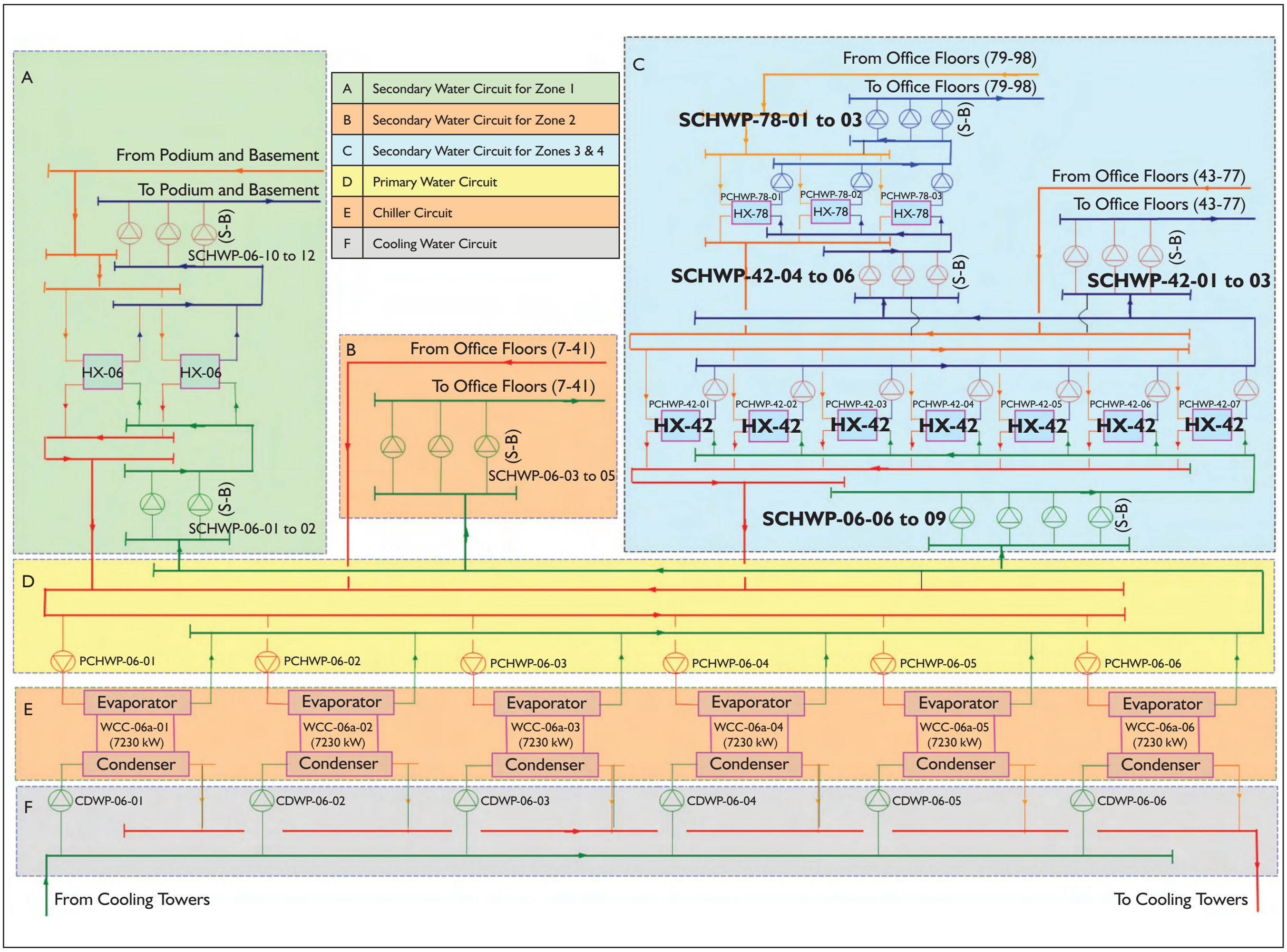

Figure 1: Schematics of the chiller and secondary chilled water systems.

nearly 6000 kPa (60 bar). The actual designed water working pressure for Zone 1 is 1600 kPa (16 bar), while the designed water working pressures for the other three zones are 2000 kPa (20 bar), respectively. Zone 2 (seventh through the 41st floor), indicated as B in *Figure 1*, is supplied with the secondary chilled water directly. For the other three zones, the heat exchangers are used to transfer the cooling energy from low zones to high zones to avoid the high water static pressure.

Zone 1 (all floors below the sixth floor) indicated as A in *Figure 1*, is supplied with the secondary chilled water through the heat exchangers located on the sixth floor, while the chilled water from chillers serves as the cooling source of the heat exchangers.

Zone 3 (43rd through 77th floor) and Zone 4 (79th through 98th floor), indicated as C in *Figure 1*, are supplied with the secondary chilled water through the first stage heat exchangers (HX-42 in *Figure 1*) located on the 42nd floor. Some of the chilled water after the first stage heat exchangers is delivered to Zone 3 by the secondary chilled water pumps (SCHWP-42-01 to 03) located on the 42nd floor. Some water is delivered to the second stage heat exchangers (HX-78 in *Figure 1*) located on the 78th floor by the secondary chilled water pumps (SCHWP-42-04 to 06) located on the 42nd floor. The water system after the second stage heat exchangers is the conventional primary-secondary chilled water system.

Zones 3 and 4 represent about 51% of the total cooling load of this building. All primary chilled water pumps in Zones 3 and 4 are constant speed pumps, while all secondary chilled water pumps are variable speed pumps. The major specification of all pumps in Zones 3 and 4 at the design condition is summarized in *Table 1*. The total design power load of all pumps in Zones 3 and 4 is 389 ton (1369.4 kW), while the total design power load of all constant speed pumps in Zones 3 and 4 is 120 ton (421.2 kW). The constant primary pumps makeup 30.76% of the total pump power in Zones 3 and 4 at the design condition.

The Original Design Configuration

In the original design, the configuration of water systems after the first and second stage heat exchangers in Zones 3 and 4 is the primary-secondary pumping paradigm. Each primary chilled water pump is dedicated to each heat exchanger to provide a relatively constant water flow rate, while the water flow rate in the secondary chilled water system varies to meet the indoor cooling load requirements. Under part load, especially

Pumps	Number*	Flow (L/s)	Head (m)	Efficiency (%)	Pow (kW)	Pow_{tot} (kW)
SCHWP-06-06 to 09	3 (1)	345	30.3	84.2	122	366
PCHWP-42-01 to 07	7 (1)	149	26.0	84.9	44.7	312.9
SCHWP-42-01 to 03	2 (1)	294	36.5	87.8	120	240
SCHWP-42-04 to 06	2 (1)	227	26.2	84.3	69.1	138.2
PCHWP-78-01 to 03	3 (1)	151	20.6	84.3	36.1	108.3
SCHWP-78-01 to 03	2 (1)	227	39.2	85.8	102	204
Total design power of all pumps in Zone 3 and Zone 4				1369.4 (kW)		
Total design power of primary pumps in Zone 3 and Zone 4				421.2 (kW) (30.76%)		

*Value in parentheses indicates number of standby pumps. Pow_{tot} in each row does not include the power of standby pumps.

Table 1: Major specifications of all pumps in Zones 3 and 4.

under light load, these primary chilled water pumps contribute a large portion of the total energy used in Zones 3 and 4. In the conventional primary-secondary chilled water systems, the primary chilled water pumps are piped and dedicated to each chiller to provide a constant water flow rate in the evaporators, achieving more reliable control and avoiding the freezing and rupturing of tubes in the evaporators.

For the heat exchangers in Zones 3 and 4, the major function of these primary chilled water pumps is to provide the circulation force to chilled water to overcome the pressure drops. Since both sides of heat exchangers are chilled water and the water temperatures are normally higher than 41°F (5°C) for this project, there is no problem of freezing and rupturing occurring in the heat exchanger tubes. To reduce the installation cost and space requirements as well as to enhance the system energy efficiency, these primary chilled water pumps can be eliminated from the original design and the variable primary water system can be designed for Zones 3 and 4.

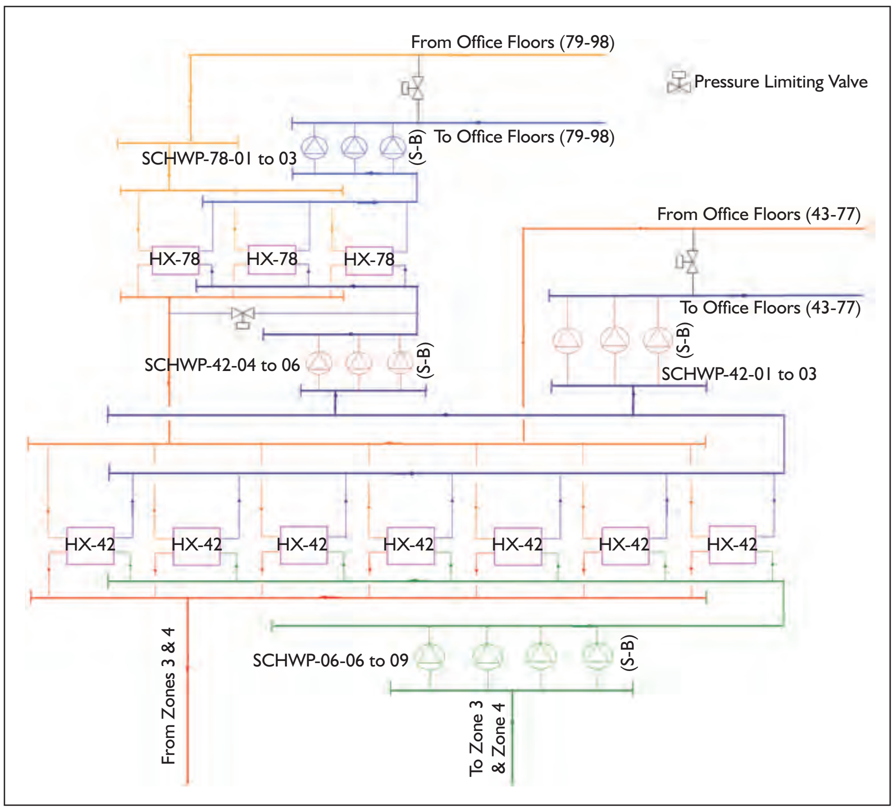

Figure 2: Water systems in Zones 3 and 4 using the alternative design configuration.

The Alternative Design Configuration

Although variable primary chilled water systems have been addressed and promoted in a number of studies,[1,2,5,7–9] primary-secondary chilled water systems are still used in many projects. These systems are simple, and personnel are familiar and experienced with them.[3] Also, there is a concern that the controls intended to prevent freezing and rupturing from occurring in chiller evaporators may cause nuisance shutdowns of chillers as a result of too-rapid decreases in chilled water flow. In the alternative design, the configuration of the primary-secondary chilled water system associated with the chillers keeps them unchanged, while the configurations of the water systems after the first and second stage heat exchangers in Zones 3 and 4 are designed as the variable primary chilled water systems.

Figure 2 shows the water systems in Zones 3 and 4 using the alternative design. In this design, the primary chilled water pumps after the first and second stage heat exchangers and their associated fittings in the original design are eliminated, and the secondary chilled water pumps in the original design are functioned as the variable primary pumps. The bypass line between the primary water loop and the second-

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ary water loop in the original design is eliminated as well. In the alternative design, a bypass line is located near the pumps, as shown in *Figure 2*, to limit the maximum pressure head on the water distribution system. A pressure limiting valve is installed on each bypass line. When the pressure difference between the two points is more than a predetermined pressure difference, the pressure limiting valve will be activated. Otherwise, the valve is closed.

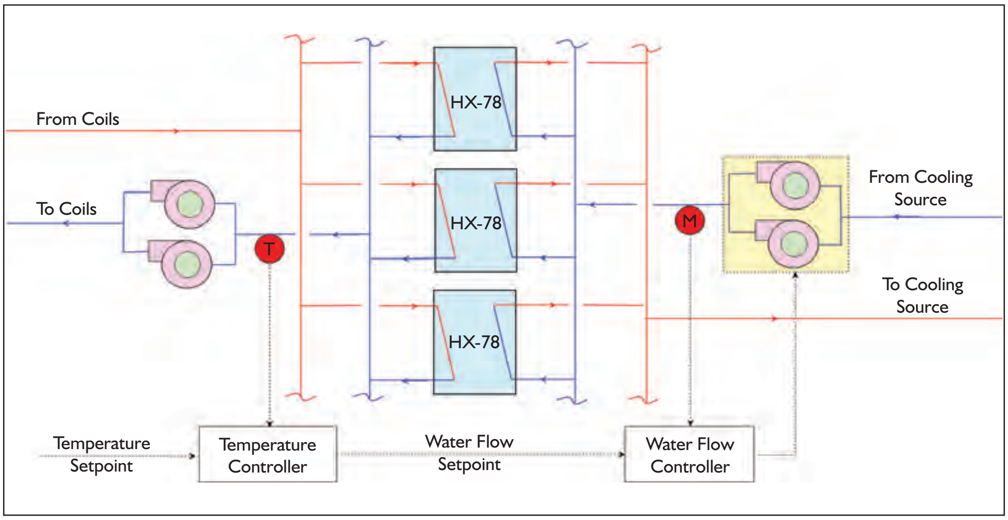

Figure 3: The speed control logic for pumps of SCHWP-42-04 to 06.

Compared to the original design, this alternative design has several distinct advantages. The installation cost and space requirements are reduced significantly due to the elimination of the primary water pumps after the first and second stage heat exchangers and their associated fittings. The system energy performance is improved since the parasitic power of these primary constant chilled water pumps is eliminated. The energy performance associated with this alternative design is evaluated and compared with the original design in the next section.

Energy Performance Evaluation

Since the building is still at the construction stage, the hourly based annual building cooling load profiles of this building

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were calculated using EnergyPlus[4] based on the design data and hourly based weather data of the typical year in Hong Kong. To predict the power consumption of variable speed pumps under various operating conditions, proper pump models are required. The pump models used in this study were comprised of polynomials representing head versus flow and speed, efficiency versus flow and speed, motor efficiency versus the fraction of the nameplate brake horsepower, and VSD (variable speed driver) efficiency versus the fraction of the nominal speed. The head and efficiency characteristics are based on the manufacturers' data at full speed operation and extended to variable speed operation using pump affinity laws.[5]

To evaluate energy performance of the original design and alternative design, a set of control strategies are required to control the operation of these pumps. In this article, simple control strategies are used and are presented briefly. The speed of the pumps distributing water to cooling coils (i.e., pumps of SCHWP-42-01 to 03 in Zone 3 and pumps of SCHWP-78-01 to 03 in Zone 4) is controlled to maintain the differential pressure at a remote location in the system at a setpoint determined to be sufficient to deliver the required chilled water flowing through all cooing coils. The speed of the pumps distributing water to heat exchangers, i.e., pumps of SCHWP-42-04 to 06, is controlled using a cascade controller, as shown in *Figure 3*. This cascade controller uses the outlet water temperature at the secondary side of heat exchangers to determine the required water flow rate with respect to the temperature setpoint and the required water flow rate is then compared with the measured water flow rate to carry out the pump speed control. In this controller, a predetermined function is embedded to set the setpoints of the outlet water temperature at the secondary side and the water temperature at the primary side of heat exchangers with proper difference, allowing the water flow rates at both sides to remain roughly the same as needed for proper control of the system.

The same control logic also is used for the pumps of SCHWP-06-06 to 09 for the same purpose. The heat exchangers and pumps are sequenced based on the water flow limits for each. Another heat exchanger is put into operation when the water flow rate of each operating heat exchanger exceeds its design water flow rate. One of the operating heat exchangers will be switched off when the water flow rate in the system is less than the total design water flow rate of (N-1) heat exchangers (the current operating number of heat exchangers is N). Another pump is put into operation when the water flow rate of each operating pump exceeds its design value. One of the operating pumps will be shut down when the water flow rate in the system is less than the total design water flow rate of (N-1) pumps (the current operating number of pumps is N).

A dead band is used in the sequence controllers of the heat exchangers and pumps for staging and destaging a heat exchanger and a pump to avoid their frequent cycling on and off. In the original design, the operation of each primary chilled water pump in Zones 3 and 4 is dedicated to the operation of the associated heat exchanger that it serves. Since the setpoint,

Pump Power	Original Design (kWh)	Alternative Design (kWh)	Savings (kWh)	Savings (%)
Annual	2,760,758.4	1,726,163.5	1,034,594.9	37.48
Spring day	8,587.7	5,392.7	3,195.0	37.20
Mild-Summer Day	10,505.8	6,490.4	4,015.4	38.22
Sunny-Summer Day	12,894.5	8,212.8	4,681.7	36.31

Table 2: Comparison of annual and daily power consumption of all pumps in Zones 3 and 4 under different design configurations.

including the differential pressure setpoint and the temperature setpoint, of each local controller significantly affects the system energy consumption, the same setpoints were used during the evaluation of energy performance of both design configurations. Most of the control and operation strategies used in this study are conventional and not the optimal strategies to be used in practice.

Based on the previous pump models and control strategies, the energy performance of both design configurations was evaluated on the virtual building system, including the cooling plant and air-conditioning systems that were constructed, particularly for the super high-rise building.[6] Using the simulated hourly based annual building cooling loads and the hourly based weather data of the typical year in Hong Kong, the annual power consumptions of the pumps in Zones 3 and 4 under two different design configurations were evaluated. *Table 2* gives the results. The annual power consumptions of pumps in Zones 3 and 4 using the original design configuration and the alternative design configuration were 2,760,758.4 kWh and 1,726,163.5 kWh, respectively. Compared to the original design configuration, the annual energy savings using this alternative design configuration was about 1,034,595 kWh, which contributes about 2% in savings of the annual total energy consumption of the overall air-conditioning system (including all pumps, chillers, cooling tower fans, AHU fans, and PAU fans) of this building.

Three typical days, which represent the typical operation conditions of the air-conditioning system in the spring, mild-summer, and sunny-summer, respectively, were selected to demonstrate more details of energy-saving potentials using the alternative design configuration. The building cooling loads are varied from 796 ton to 7,535 ton (2,800 kW to 26,500 kW), from 1,308 ton

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to 8,985 ton (4,600 kW to 31,600 kW), and from 1,507 ton to 10,805 ton (5,300 kW to 38,000 kW) in the selected typical spring day, mild-summer day, and sunny-summer day, respectively. Compared to the original design, the alternative design can save about 3,195.0 kWh (37.20%), 4,015.4 kWh (38.22%) and 4,681.7 kWh (36.31%) in the typical spring day, mild-summer day and sunny-summer day, respectively. The hourly based pump power consumptions under two different design configurations in the typical sunny-summer day are also showed in *Figure 4*. At part load, the contribution of the parasitic power of the primary pumps in the original design to the total power consumption of the pumps in Zones 3 and 4 would be more significant.

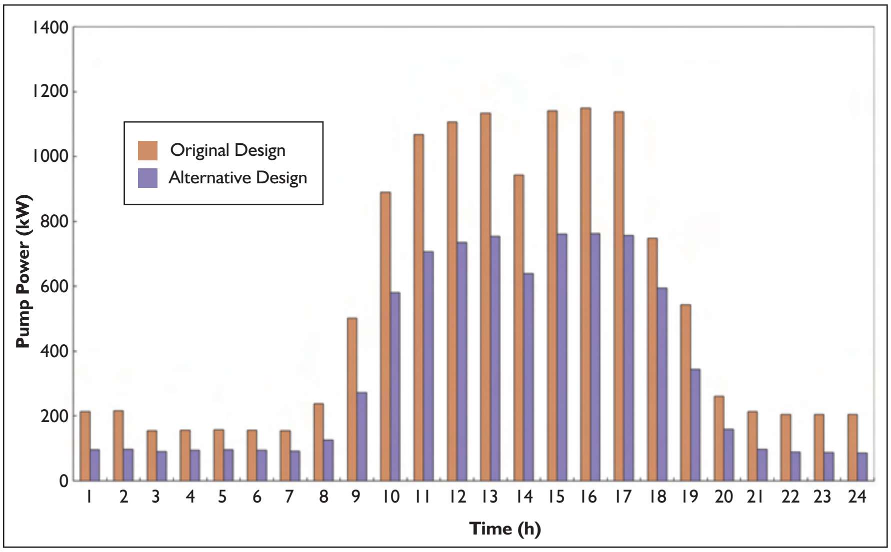

***Figure 4:** Comparison of hourly based pump power consumptions between two design configurations in the typical sunny-summer day.*

The hourly based pump power consumption of the original design is always significantly higher than that of the alternative design. These preliminary results illustrate that this alternative design can provide significant energy savings in this building as compared to the original design. The power consumptions presented throughout this article includes the power consumptions of all pumps in Zones 3 and 4 only.

The practical installation of the chilled water pumping systems can operate under these two design configurations because the alternative design was proposed at the construction stage. One standby primary chilled water pump at each primary set is eliminated and the associated pipeline is replaced by a bypass line, allowing the chilled water system to operate without using the constant primary pumps. When the manual valves installed on these bypass lines are shut off, the chilled water system can operate according to the original design configuration. The secondary chilled water pumps in the original design can provide sufficient pump head to handle the pressure losses previously handled by the primary pumps since the secondary chilled water pumps in the original design are oversized.

Conclusions

An alternative design configuration for the secondary chilled water system of a super high-rise building is presented in this article and implemented in the building to achieve more energy savings. The preliminary energy performance evaluation results show that a significant amount of pump energy can be saved when using this alternative design. Compared to the original primary-secondary design configuration, the annual energy savings using this alternative design configuration for this building is about 1,034,594 kWh. Both alternative design configurations are implemented in the super high-rise building. Their operational performance, implementation issues, and control issues, as well as their comparisons in practical application, will be reported in the near future.

Acknowledgments

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